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Electromagnetic Measurement and Modeling Techniques for Microwave Ablation Probes

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Abstract—**Broadband scattering parameter measurement of a commercially available microwave ablation probe over the course of a 10 minute 45 Watt ablation cycle within ex-vivo bovine liver tissue is performed. Measurement results are compared to finite difference time domain simulation of the probe in non-ablated and fully ablated tissue geometries. Measurement and simulation results agree well from 0-3 GHz demonstrating the accuracy of a multi-compartmental ablation geometry modeling technique. The electromagnetic modeling technique presented in this paper introduces a useful design tool for optimizing microwave ablation probes without the need for multi-physics simulation packages. The relevance of tissue complex permittivity change with temperature to microwave ablation probe performance is discussed.**

I. INTRODUCTION

MICROWAVE energy induced tissue heating by near field probes operating in the industrial, scientific and medical (ISM) frequency band is emerging as a common thermal treatment of liver tumors. Also known as microwave tumor ablation, tissue temperatures are elevated above 60°C through water molecule agitation to incite cell death as a result of coagulative necrosis [1]. Microwave ablation (MWA) offers an alternative therapy to radio frequency ablation (RFA). MWA may offer key advantages over RFA including higher treatment temperatures, larger active heating zone and reduced susceptibility to ablation zone distortion when used near large vasculature [2]. Another major advantage of MWA is its ability to deliver energy to tissue despite inter-ablation temperatures above 100°C. RFA cannot effectively deliver energy into tissue above 100°C. MWA probe efficiency measured as the ratio of reflected power to forward power (scattering parameter) is however affected by the dielectric properties of the tissue within the ablation zone which significantly change over an ablation procedure due to temperature rise and associated tissue dehydration [3-7].

This study demonstrates successful small-signal measurement of MWA probe broadband scattering parameters periodically over the duration of a high power microwave ablation cycle and introduces an electromagnetic modeling technique which accurately represents the broadband scattering parameters of a MWA probe at the onset and completion of an ablation cycle without the need for a multi-physics simulation software package.

II. METHODS

Bench work for this study was performed in fresh ex-vivo bovine liver tissue. Tissue was immediately placed on ice for transport and then stored at a temperature between 15-17°C up to the time of use, which was within 24 hours of excision.

Ablations were performed with the Evident ™ MWA Surgical Antenna (Covidien EbD, Boulder, CO) over 10 minutes within the dome of a liver to avoid major vasculature. Microwave power delivery to the probe was provided by a commercially available signal source and power amplifier in a manner analogous to setting the Evident ™ MW Ablation Generator (Covidien EbD, Boulder, CO) to 45 Watts. Small-signal broadband one-port scattering parameter measurement of the ablation probe within the tissue environment was performed each minute during the ablation cycle using a network analyzer. A network of automated switches was used to isolate the sensitive measurement equipment from the high power energy source and enable approximately ten millisecond interruption of energy delivery to the tissue during measurement sweeps. Short, open, and load precision calibration of the network analyzer was performed at proximal end of the surgical probe's semi-rigid coaxial cable.

Finite-difference time-domain (FDTD) electromagnetic simulation of the Evident ™ MWA Surgical Antenna within non-ablated and ablated ex-vivo bovine liver was performed using Computer Simulation Tools: Microwave Studio (CST, Darmstadt, Germany). Material electrical property definition around the probe for the non-ablated model was defined with complex permittivity values consistent with fresh 17°C ex-vivo bovine liver tissue. A multi-compartmental geometry was used to model the fully ablated tissue around the MWA probe. Data previously measured at Covidien EbD [6] during microwave ablation including tissue temperature versus radius from the probe over time and complex permittivity versus tissue temperature were used to define each compartment's geometrical and electrical parameters. Table 1 displays the inner and outer diameters of each compartment. Table 2 displays the temperature ranges associated with each compartment. Table 3 displays the compartment's associated complex permittivity values at 1 GHz resulting from second order dispersion fitting to measured data.

Fig. 1 displays the geometry of the multi-compartmental ablation model. Each compartment is a cylindrical shell with hemispherical end caps. Two cylinders of char are

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included in the geometry around the distal tip of the probe as well as around the feed point of the probe, consistent with Evident ^{TM} MWA Surgical Antenna ablation performance in ex-vivo bovine tissue. Material definition around the ablation boundary is consistent with fresh ex-vivo bovine liver tissue. The non-ablated model is consistent with defining the entire geometry around the probe with the fresh tissue electrical properties.

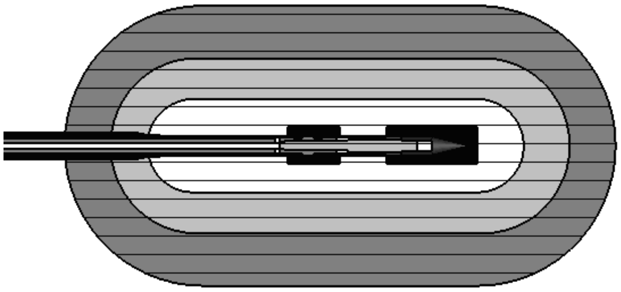

Fig. 1: Cross section of ablated tissue model. White: first layer, Light Grey: second layer, Dark Grey: third layer, Black: char.

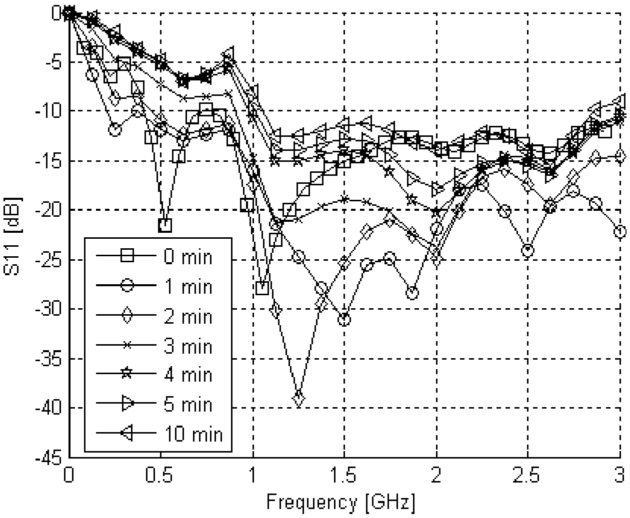

Fig. 2: Measurement of MWA probe broadband scattering parameter over the course of a 10 minute 45 Watt ablation in ex-vivo bovine liver tissue.

III. RESULTS

Electrical performance of the MWA probe used in this study varied considerably over the 10 minute ablation cycle. Fig. 2 displays the measured scattering parameter of the probe from 0-3 GHz prior to and at each successive minute during an ablation cycle. Data from minutes 6, 7, 8, and 9 are omitted to make the graph discernable and due to their similarity to the data of minute 5 and 10. Table 4 displays tabulated data of the scattering parameter (S11) at the 915 MHz operating frequency during minutes 0, 1, 2, 3, 4, 5 and 10. Fig. 3 and 4 display the scatting parameter simulation results of the non-ablated and fully ablated FDTD models with the corresponding 0 minute and 10 minute measured data.

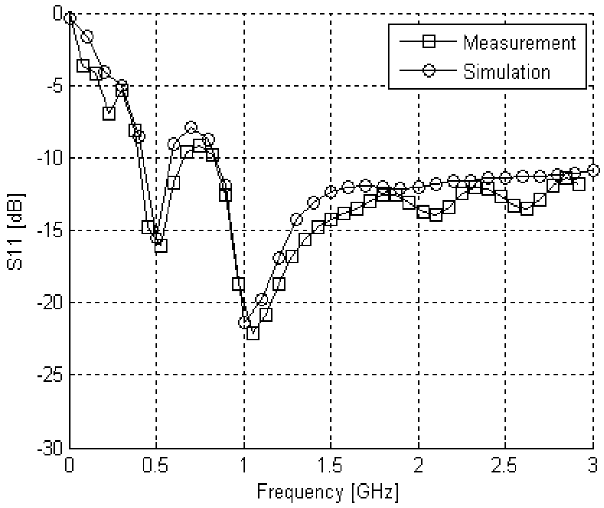

Fig. 3: Simulation and measurement broadband scattering parameter data of MWA probe in 17°C fresh ex-vivo bovine liver tissue.

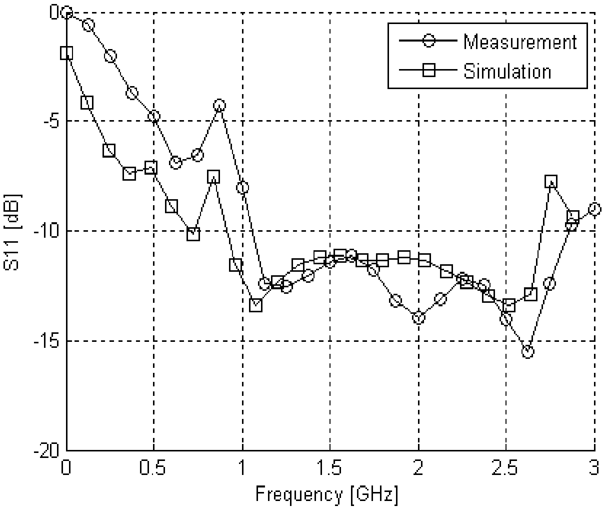

Fig. 4: Simulation and measurement broadband scattering parameter data of MWA probe in fully ablated ex-vivo bovine liver tissue.

IV. DISCUSSION

The Evident ^{TM} MWA Surgical Antenna probe is optimally designed to the complex permittivity of metastatic and primary liver tumor tissue which have similar permittivity values to fresh 17°C ex-vivo bovine liver tissue [3]. Initially, the MW probe is well matched to the 50 ohm energy delivery system at the 915 MHz frequency of operation, delivering 94 percent of the forward microwave power to the tissue. After one minute, the probe delivers 76.6 percent of the forward power and by the end of the ablation cycle the probe delivers 38.3 percent of the forward power to the tissue. The reduction in probe efficiency as an ablation cycle progresses is due to temperature rise induced drop in complex permittivity of the tissue within the near field of the probe. The real part of permittivity, or dielectric constant, decreases by a factor of 10 (see Table 3) and imaginary part of permittivity, or dielectric loss factor, decreases by a factor of 6 for tissue which exceeds 100°C. The remaining tissue within a 5 mm radius of the probe radiating section axis drops in complex permittivity by a factor of 5 (real part) and 3 (imaginary part). These drops in permittivity in close proximity to the probe radiating section significantly influence the probe impedance and therefore the probe's efficiency.

The simulated broadband scattering parameter behavior of the MWA probe presented in this study match well with measurement for both the non-ablated and fully ablated models (see Fig. 3 and Fig. 4). The method of ablation modeling presented in this paper can be used to accurately represent the electrical behavior of MWA probes in a variety of tissue states without a multi-physics coupling of thermal, fluid and electromagnetic tissue dynamics. Although this simplified method is not predictive of device tissue effect, it can be used to rapidly optimize MWA probe dimensions within a known tissue state by considerably reducing simulation times over comparable multi-physics software simulation times. Pure electromagnetic solver software, such as CSTMS, tends to offer user friendly parameterization tools for the model geometry, further simplifying design optimization.

V. CONCLUSION

Tissue dielectric constant and loss factor values within the near field of MWA probes significantly influence device impedance at microwave frequencies. While Evident^{TM} MW Ablation Surgical Antennas have demonstrated performance experimentally and clinically, it is clear that utilizing the methods discussed in this work will aid in the future design and manufacture of more efficient MWA probes.

ACKNOWLEDGMENT

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TABLE I
MODEL COMPONENT DIAMETERS [6]

Component	Inner Diameter (mm)	Outer Diameter (mm)
Char	NA	5
First Layer	NA	10
Second Layer	10	20
Third Layer	20	30
Non-ablated Tissue	30	NA

TABLE II
MODEL COMPONENT TEMPERATURE RANGES [6]

Component	Maximum Temperature (°C)	Minimum Temperature (°C)
Char	NA	100
First Layer	100	90
Second Layer	90	70
Third Layer	70	50
Non-ablated Tissue	50	17

TABLE III
MODEL COMPONENT COMPLEX PERMITTIVITY [6]

Component	Relative Permittivity	Loss Factor
Char	5.2	2.5
First Layer	18.1	3.3
Second Layer	32.7	15.2
Third Layer	45.0	22.3
Non-ablated Tissue	52.6	16.4

TABLE IV
PROBE SCATTERING PARAMETER AND EFFICIENCY DURING AN ABLATION CYCLE

Minute	S11 (dB)	Efficiency (%)
0	-24.5	99.6
1	-12.6	94.5
2	-11.9	93.5
3	-9.2	88.0
4	-6.3	76.6
5	-5.4	71.2
10	-4.2	62.0